Water Conservation Science and Engineering (2021) 6:37–43
https://doi.org/10.1007/s41101-020-00100-x

ORIGINAL PAPER

Irrigation Management Effects on Crop Water Productivity for Maize Production in the Texas High Plains

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Received: 2 December 2019 / Revised: 3 November 2020 / Accepted: 1 December 2020 / Published online: 13 January 2021

Abstract

Corn (*Zea mays* L.) was grown under full and deficit irrigation in two research field locations near Bushland, TX, in 2018 to compare seasonal water use of two irrigation management approaches. Full irrigation was achieved in both fields by allowing no more than 55% depletion of plant available soil water. However, irrigation depth and frequency were different in each field. The USDA-ARS Conservation and Production Research Laboratory (CPRL) weighing lysimeter fields were generally irrigated twice weekly using irrigation depths ranging from 19 to 32 mm. The Texas A&M AgriLife Research Emeny field was irrigated only once per week, having greater application depths ranging from 35 to 42 mm. Deficit irrigation treatments of 75% of full irrigation were also performed in both research fields. Yield and crop water productivity values for the 100 and 75% lysimeter field irrigation treatments were greater than corresponding values for the Emeny field. Emeny field yields may have been slightly reduced by heat stress incurred between irrigations during early grain fill whereas more frequent irrigations on the lysimeter fields may have reduced heat stress during that period. Results from this study suggest that evaporative losses associated with the more frequent, smaller application depth irrigations on the lysimeter fields did not contribute to appreciably lower CWP values, as losses were likely mitigated by the rapid development of the corn canopy. These findings suggest that corn yield is principally dependent upon seasonal water inputs and losses from frequent, smaller depth irrigations are minimal outside of incomplete canopy conditions.

Keywords Corn · Deficit irrigation · Irrigation frequency · Irrigation scheduling

Introduction

Corn (*Zea mays* L.) production in much of the southern Great Plains relies on the Ogallala Aquifer for irrigation water to supplement inadequate precipitation. Decades of pumping with limited recharge have resulted in declining water tables and limited well capacities in most areas of the Texas High Plains (THP) [8, 11]. As water resources continue to decline, producers may shift acreage to less water-intensive crops such as cotton (*Gossypium hirsutum*) (Colaizzi et al., 2009; [1]). However, grain corn remains a major irrigated crop in the northern THP with localized silage production in the southern THP associated primarily with the growing dairy industry. Advances in drought tolerant corn hybrids have been shown to produce profitable yields under both full and deficit irrigation [6, 7]. Still, prudent irrigation scheduling remains an effective means for limiting water losses by preventing excessive evaporation, runoff, and percolation below the rooting zone. Irrigation scheduling approaches are commonly based on estimates of crop evapotranspiration ET_c or soil water depletion. However, irrigation depth and frequency are largely determined by well and irrigation system capacities.

Several studies have examined the effects of irrigation management on corn grown in the southern Central Plains

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region. Eck [2] reported the effects of irrigation timing and duration of water deficit periods on corn growth and yield. Howell et al. [9] compared full and deficit irrigation using low energy precision application (LEPA) methods used with furrow diking. They showed that LEPA was efficient at partitioning applied water into crop water use. The application efficiency, or effective use of irrigation, can be defined as the amount of water that enters the soil profile and is available to the crop. Sprinkler irrigation application efficiencies are commonly estimated at 90 to even 95%. Even with these high efficiencies, intrinsic evaporative losses occur with each irrigation application [5, 12]. These losses are dependent upon climate, soil texture, canopy height, spray pattern and height, and droplet size. They also vary temporally with crop growth and canopy development. It stands to reason that greater cumulative evaporative losses would be incurred with an increased number of seasonal irrigations. However, the confluence of the aforementioned crop and irrigation system conditions can make comparisons challenging. In general, data from multiple growing seasons are desired for such comparisons of water management regimes. However, corn grown under two irrigation scheduling approaches in the relatively dry 2018 growing season presented an ideal opportunity for comparison. We present agronomic and crop water productivity (CWP) data collected from two research fields in the Texas High Plains, one using relatively high frequency, low application depth irrigation and the other using low frequency, high application depth. Yield and CWP values for fully irrigated and deficit irrigated treatments in both fields were presented.

Materials and Methods

Field Study Sites and Agronomy

Modern drought-tolerant corn hybrids were grown under sprinkler irrigation at the USDA-ARS Conservation and Production Research Laboratory (CPRL) near Bushland, TX (35° 11′ N, 102° 6′ W, 1170 m elevation above MSL) in 2018. The hybrids were grown using different irrigation levels in two research fields: the ARS large weighing lysimeter fields and the Texas A&M AgriLife Research Emeny field (Fig. 1). The Emeny field was located approximately 2.5 km due east of the lysimeter fields. Soils in both fields were Pullman silty clay loam (fine, mixed, superactive, thermic Torrertic Paleustoll) having slopes of less than 0.3%. The slowly permeable soil has a dense Bt horizon (0.3 to 0.5 m depth) and a caliche layer at approximately 1.4 m depth that presents a texture contrast that restricts water movement in some seasons. The regional climate is classified as semiarid with average annual precipitation totaling ~460 mm. Seasonal extremes are characterized by warm summers and cold winters. Annual pan evaporation exceeds 2400 mm [10]. Corn grown at both locations was managed for high yield potential using practices common to the Texas Panhandle, including nitrogen and phosphorus fertilizer applications based on commercial soil testing.

Lysimeter Fields

The lysimeter field was divided into four quadrants, designated according to their position relative to the cardinal points, NE, NW, SW, and SW, with a large weighing lysimeter positioned in the center of each field. Only the NW and SW fields were considered herein since these were irrigated by sprinkler (Fig. 1). Pioneer 1151AM (P1151) corn hybrid was planted in the west fields on DOY 144 at 86,486 seeds ha^{-1} on 0.76 m row spacing, with emergence occurring on DOY 151. The E-W oriented interrows were furrow diked on DOY 170. The fields were irrigated using a N-S oriented 10-span, 455-m linear move sprinkler equipped with mid-elevation spray application (MESA) drops positioned approximately 1.0 m above the soil surface, each fitted with a 70-kPa regulator. Nominal system flow of 3028 L min^{-1} was supplied by a 37-kW centrifugal pump with nominal lateral head and end pressures of 241 and 138 kPa, respectively. Soil water content was measured throughout the season using a calibrated neutron probe and depth control stand [4]. Measurements from both the lysimeter monoliths and surrounding fields were compared to assess soil water deficits and irrigations were scheduled accordingly. Measurements were taken once weekly, and generally 1 day prior to the initial irrigation of the week, weather permitting. Irrigations were scheduled to allow no more than 55% depletion of plant available water in the rooting zone, defined as a depth 1.5 m from the surface. Both fields were fully irrigated using a uniform nozzle package during early vegetative growth stages to ensure good crop establishment. Beginning on DOY 178, irrigation on the SW field was ~75% of that of the NW field, achieved by a reduction in nozzle size. Typically, two irrigations of ~25.4 mm were applied per week once the canopy had closed. Plant samples were taken from each field approximately every 2 weeks for leaf area index (LAI), aboveground biomass, and ear weights, when appropriate. Hand harvest samples and combine yield samples were collected from each field at the end of the season.

Emeny Field

Another drought-tolerant corn hybrid, Pioneer 1366 (P1366), was planted in the semicircular Emeny field on DOY 138. Irrigation was supplied by a seven-span, ~370-m center pivot system equipped with low-elevation spray application (LESA) spray plates positioned approximately 0.5 m above the soil surface and each having a 41-kPa regulator. The sprinkler was nozzled for uniform

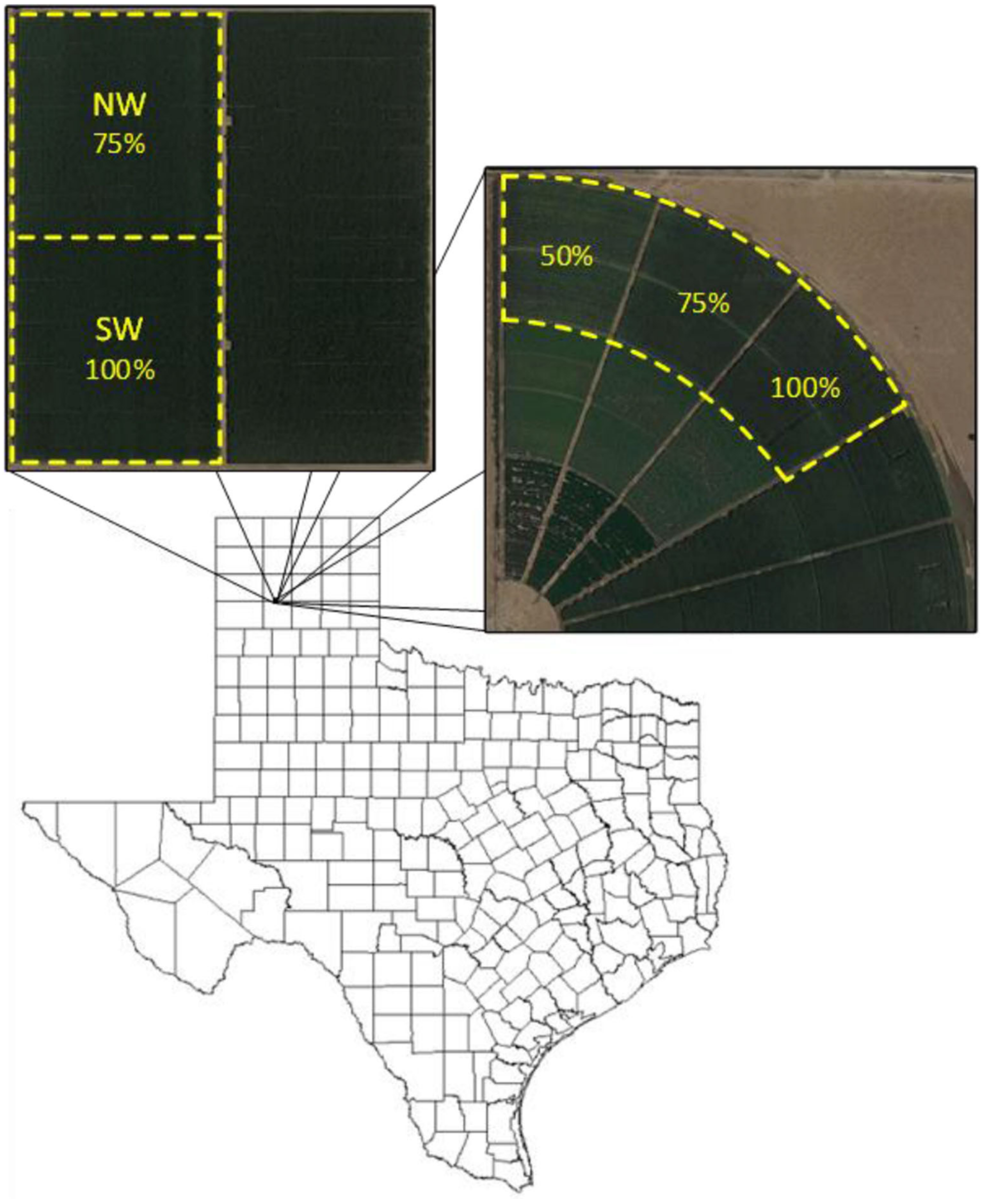

Fig. 1 Location and orientation of the CPRL weighing lysimeter fields (left) and the Texas A&M AgriLife Emeny center pivot field (right) located near Bushland, TX. The fields are designated according to irrigation level, 100% (full irrigation) and 75% and 50% (deficit irrigation)

application along the lateral for a nominal flow rate of 2271 L min^{-1}, with system head and end pressures of 103 and 83 kPa, respectively. Flow was provided by a 19-kW submersible pump governed by a variable frequency drive (VFD) controller. Plots were delineated as three 20-degree wedges of ~2.4 ha each, and irrigation treatments were achieved by varying machine travel speed. The P1366 was grown in both spans 6 and 7. Irrigation treatments were defined as targeting irrigations to supply 100, 75, and 50% of crop water requirements, with corresponding plant populations of 83,274, 78,085, and 62,517 plants ha^{-1}. Soil water content was measured weekly to 1.5 m depth, using two neutron probe access tubes installed near the center of each treatment plot. Daily crop evapotranspiration (ET_c) was also estimated using a crop coefficient and standardized daily reference evapotranspiration (ET_{os}) values form a nearby weather station (ASCE, 1995) for comparison with soil water depletion data. Periodic hand samples were taken from the P1366 plots along with hand and combine samples at harvest.

Irrigation Management

A prolonged dry period following a wet early spring in 2018 presented challenges for planting as upper soil layers were relatively dry in both fields. As such, irrigations began shortly after planting in both fields to facilitate germination. Both fields also experienced inconsistent plant growth following germination as irrigation water distribution in the near surface soil layers was not uniform

Table 1 Corn yield, water balance, and crop water productivity for irrigation treatments on the lysimeter and Emeny fields

Field and treatment	Yield (kg ha^{-1})	Irrigation (mm)	Precipitation (mm)	Soil depletion (mm)	Total water (mm)	CWP (kg m^{-3})
Emeny 100	11,101	487	92	80	671	1.65
Emeny 75	9809	395	92	111	610	1.61
Emeny 50	4893	303	92	120	527	0.93
Lysimeter 100	12,288	559	87	38	708	1.74
Lysimeter 75	11,471	452	87	84	647	1.78

due to preplant tillage operations. Irrigation treatments to satisfy 100% of plant ET requirements were included in both fields although deficit irrigation treatments were also performed. Irrigation scheduling however was different for each field, with the lysimeter field receiving more frequent irrigations of less depth and the Emeny field receiving fewer irrigations but with greater application depths. This was due, in part, to differences in the

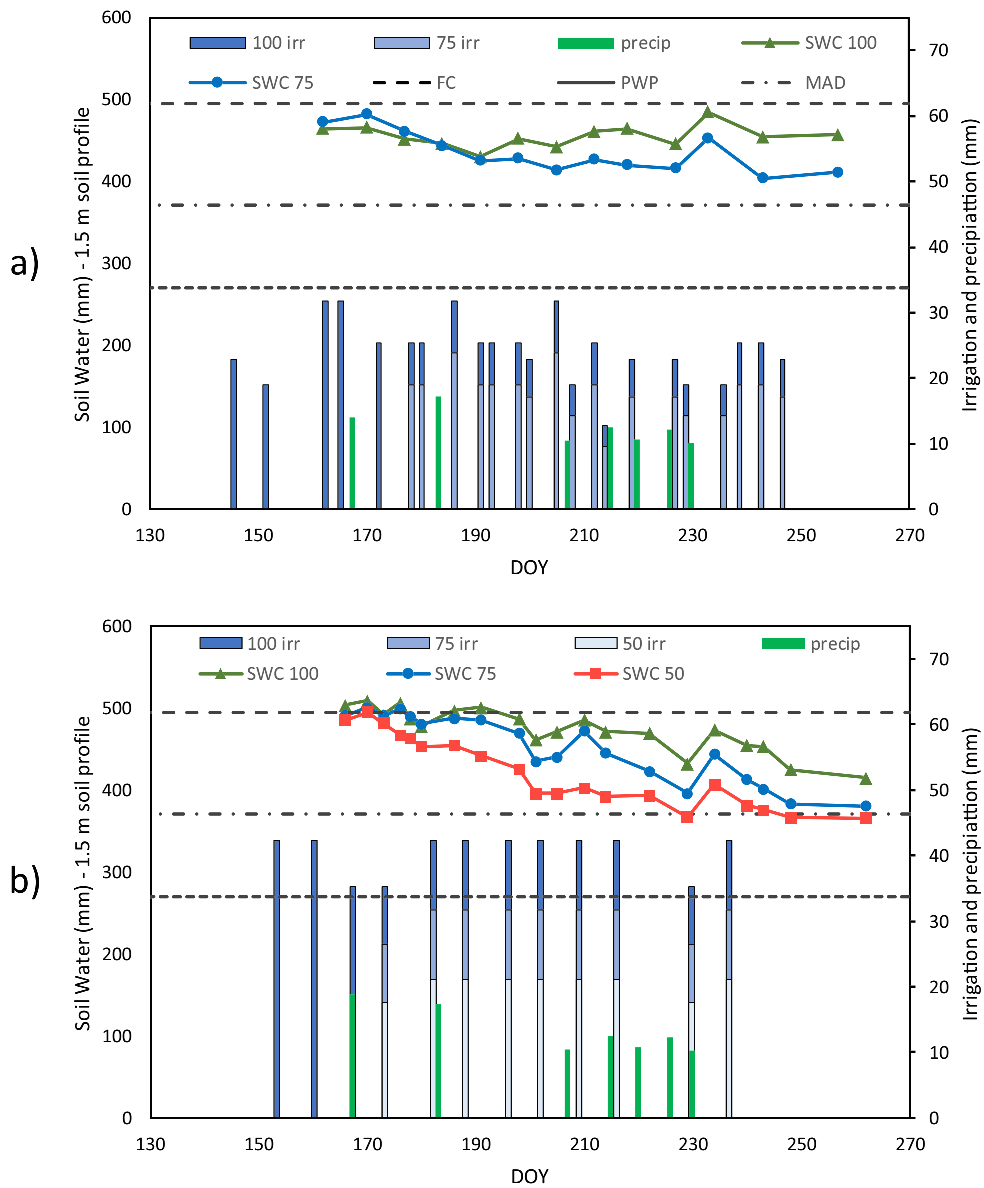

Fig. 2 Soil profile water to a depth of 1.5 m measured by neutron probe and irrigation freqency and depth for corn grown in **a** the lysimeter fields and **b** the Emeny fields. Precipitation events are also shown

irrigation machines, and also to scheduling constraints associated with water infrastructure limitations. Several irrigation systems, including the lysimeter field lateral and the Emeny center pivot, were supplied by a small surface reservoir that was filled by groundwater pumping. Withdrawal rates often exceeded inflow during simultaneous irrigations, so irrigation scheduling was required to allow for periodic filling of the reservoir to ensure all research fields were irrigated. In the absence of precipitation, the lysimeter fields generally received two irrigations a week during mid-season, with targeted application depths of approximately 25.4 mm. These irrigations required approximately 12–13 h to complete. Irrigations occurred during daytime hours to facilitate periodic operational checks of the linear move system. Consequently, irrigations on the Emeny field occurred weekly, but with greater application depths ranging from 35.3 to 42.3 mm.

Results and Discussion

Irrigation and Soil Water Balance

Twenty-three irrigations were applied on the lysimeter fields in 2018. Total seasonal targeted irrigation on the SW field was 559 mm and on the NW field 452 mm. Estimated seasonal soil water depletion for the SW and NW fields was 38 and 84 mm, respectively (Fig. 2a). Combined with seasonal precipitation of 87 mm, total seasonal water use for the SW and NW lysimeter fields was 707 and 646 mm, respectively. Each of the 10 spans under the linear move system was harvested using a combine and used to calculate yield values. Spans 1–5 were in the deficit irrigated NW lysimeter field while the fully irrigated SW field was covered by spans 6–10 (Fig. 3). Yield values from the three center spans in each field, spans 2–4 for the NW and spans 7–9 on the SW, were averaged (Table 1). Average yield values for the SW and NW fields were 12,288 kg ha^{-1} and 11,471 kg ha^{-1}, respectively.

Only twelve irrigations were applied to the Emeny field in 2018. Targeted seasonal irrigation totaled 487 mm for the 100% treatment, representing 87% of that applied on the fully irrigated lysimeter field. Irrigation totaled 395 and 303 mm for the 75% and 50% treatments, respectively (Table 1). Soil water depletion for the 100% treatment was less than that for the corresponding treatment in the lysimeter field early in the season (Fig. 2a, b). However, small late-season precipitation events helped reduce soil water depletion later in the season, with seasonal precipitation totaling 92 mm on the Emeny field (Fig. 3b). Soil water depletion plots relative to the MAD value were somewhat understated as neutron probe measurements were often taken several days prior to irrigation events, which precluded the capture of the lowest depletion values. This is in contrast to the plots for the lysimeter fields. Irrigation was terminated 10 days earlier for the Emeny field than for the lysimeter field, resulting in greater depletion of soil water in the Emeny field at the end of the season. Total seasonal water use for the 100% treatment on the Emeny field was 971 mm, or 95% of that of the fully irrigated SW field. Total seasonal water use for the 75 and 50% treatments in the Emeny field was 610 and 527 mm. respectively. Three combine harvest samples were taken from each of the irrigation treatments in the Emeny field. The sample area totaled 23.2 m^2, achieved by harvesting two adjacent rows at a length of 15.2 m. Average combine yield values for the 100, 75, and 50% treatments were 12,250, 9809, and 4893 kg ha^{-1}, respectively. A plot of average dry yield and seasonal water use for all treatments from both fields approximated a curvilinear relationship. Fully irrigated yield from the SW field was greatest, using 36 mm

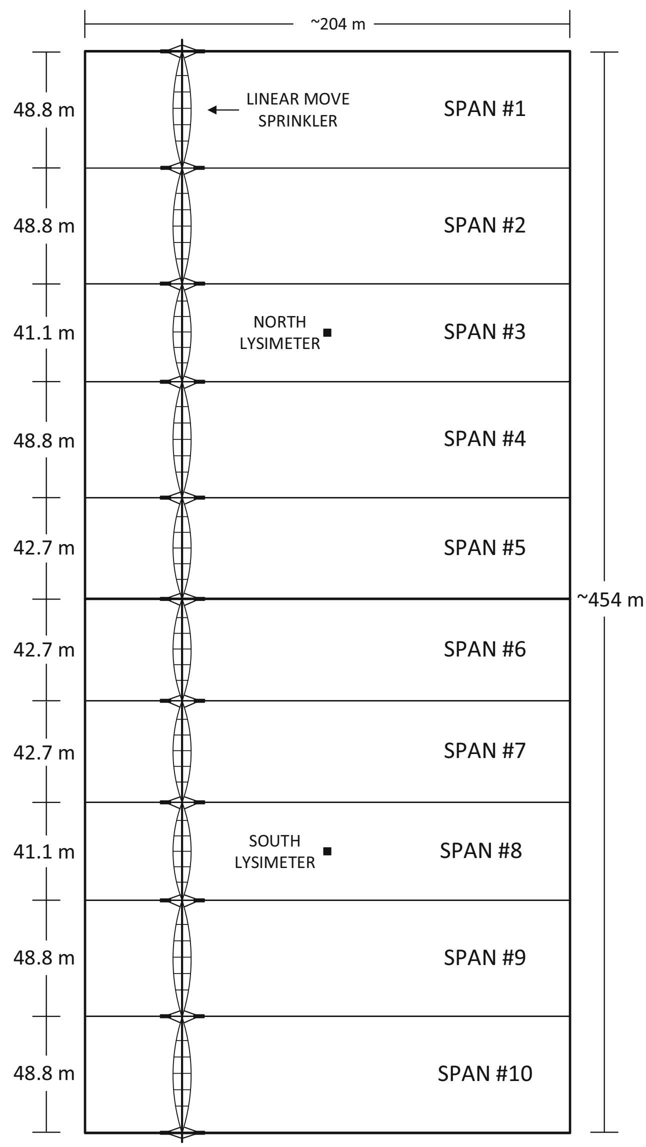

Fig. 3 Schematic drawing illustrating the relative size and position of sprinkler spans within northwest and southwest lysimeter fields, irrigated by a lateral move sprinkler

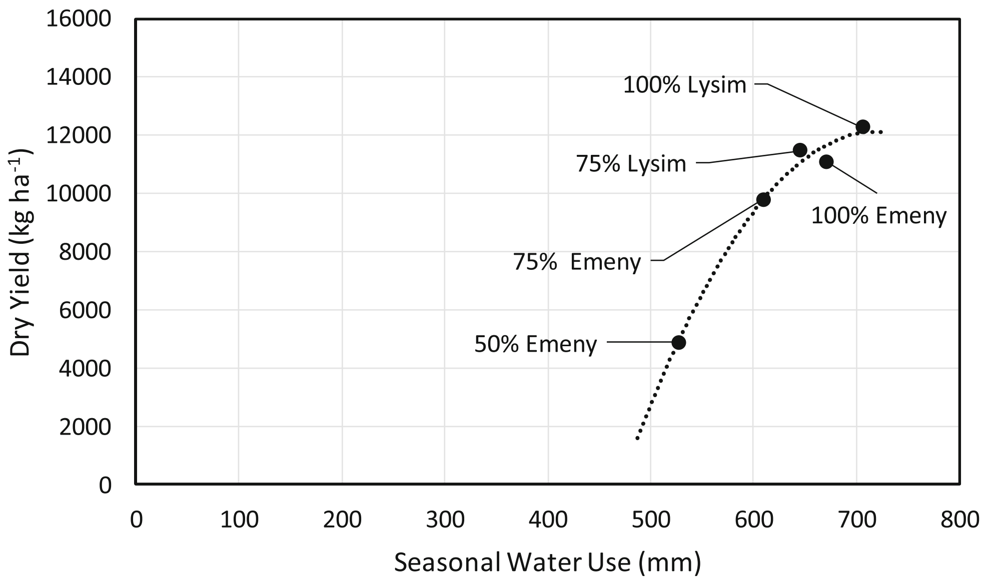

Fig. 4 Dry yield response to seasonal water associated with irrigation treatments at the CPRL west lysimeter field and the Texas A&M AgriLife Research Emeny field

more water than the 100% treatment in the Emeny field (Fig. 4). The 75% treatment yield on the NW field approximated that of the 100% treatment on the Emeny field, using ~ 25 mm less water. The 75% treatment in the NW field used 36 mm more than its Emeny counterpart, with a proportional difference in yield, resulting in an additional 1662 kg ha^{-1} for the NW field. The 50% treatment achieved an unexpectedly high average yield of 4893 kg ha^{-1} on 527 mm of water, likely benefitting from late-season precipitation.

Crop Water Productivity

The CWP is generally defined in agronomy as water use efficiency (WUE) using the following equation [13].

$$\mathrm{WUE} = \frac{\text{Crop yield (typically economic yield)}}{\text{Water used to produce the yield (ET)}} \tag{1}$$

Where crop yield is expressed in g m^{-2} and water used is expressed in mm, with resulting CWP having units of kg m^{-3} on a unit water volume basis. Values of CWP were greatest for the 100% and 75% treatments in the lysimeter fields at 1.74 and 1.78 kg m^{-3} (Table 1), respectively. Corresponding values for the 100% and 75% treatments in the Emeny field were 1.65 and 1.61 kg m^{-3}. No significant difference ($\alpha = 0.05$) was observed between CWP values for the 100 and 75% treatments in lysimeter or Emeny field. The CWP for the 50% Emeny treatment was 0.93. Decreased CWP values for the 100% Emeny field may be partially due to reduced yield resulting from plant stress during a particularly hot period spanning DOY 222–229. Although the lysimeter fields experienced this same weather, the greater frequency of irrigation there likely reduced the deleterious effects of heat stress (e.g., [3]). However, yields not much greater than 1150 kg ha^{-1} can be realistically expected from ~ 672 mm of seasonal water. Water use efficiency values for the 100 and 75% treatments were greater for the lysimeter fields than for the Emeny despite the greater drop height and evaporative losses associated with MESA.

Conclusions

Data from this study suggest that irrigation frequency has some impact on CWP corn grown under sprinkler irrigation, even in heavier soils with good water holding capacity. This is similar to findings of Evett et al. [3]. Although greater amounts of evaporation from bare soil are almost certainly attributed to more frequent irrigations during periods of incomplete canopy, the number of such events is limited due to the relatively rapid development of corn vegetative stages. Evaporative losses are likely further mitigated once crop height surpasses that of the sprinkler drops, which is consistent with findings of Evett et al. [5] who compared MESA irrigated corn ET, yield, and CWP with that for subsurface drip irrigated corn. Results from this study indicate that evaporative losses associated with smaller, more frequent irrigations of corn are not appreciably greater than those associated with greater, less frequent irrigations, with differences limited to early season vegetative stages. These findings suggest that corn yield is principally dependent upon seasonal water inputs and losses from frequent, smaller depth irrigations are minimal outside of incomplete canopy conditions.

Acknowledgments This research was supported in part by the Ogallala Aquifer Program, a consortium between USDA-Agricultural Research Service, Kansas State University, Texas A&M AgriLife Research, Texas A&M AgriLife Extension Service, Texas Tech University, and West Texas A&M University.

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Conflict of Interest The authors declare that there is no conflict of interest.

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